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SENSOR INTEGRATION, MANAGEMENT AND DATA FUSION CONCEPTS IN A NAVAL COMMAND AND CONTROL PERSPECTIVE

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SENSOR INTEGRATION, MANAGEMENT AND DATA FUSION CONCEPTS IN A NAVAL COMMAND AND CONTROL PERSPECTIVE

by

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ABSTRACT

Sensing techniques are employed in military systems as the primary means to gain knowledge about the external environment, or to update and refine such knowledge. Typically, as a result of their intrinsic shortcomings, single sensor systems have limited capabilities for resolving ambiguities and providing consistent descriptions of the sensed environment. Intelligent military systems thus make use of multiple sensors in order to satisfy the extensive need for precise and timely information. Multi-sensor systems aim to overcome the shortcomings of single sensors by employing redundancy and diversity. The appropriate integration and management of several sensors, and the intelligent use of the resulting optimum data sets through data fusion, should provide an efficient and operationally valuable approach for military systems. The aim of this document is to present a framework for addressing sensor integration, management and data fusion (SIMDF) in the perspective of its relationship to command and control.

RÉSUMÉ

Les techniques sensorielles sont utilisées dans les systèmes militaires comme moyen principal d'obtenir des connaissances sur l'environnement externe ou encore pour mettre à jour et raffiner ces connaissances. Étant donné leurs défauts intrinsèques, les systèmes à capteur unique ont des capacités limitées pour résoudre les ambiguïtés et fournir des descriptions cohérentes de l'environnement observé. Les systèmes militaires intelligents utilisent donc des capteurs multiples pour satisfaire les importants besoins d'information précise au moment opportun. Les systèmes multicapteurs visent à surmonter les défauts des capteurs uniques en employant la redondance et la diversité. La juste intégration et la gestion de plusieurs capteurs, et l'utilisation intelligente par la fusion de données des ensembles de données optimales qui en résulte devraient fournir une approche efficace et d'une grande valeur opérationnelle pour les systèmes militaires. Le but de ce document est de présenter un cadre pour aborder l'intégration, la gestion et la fusion des données de capteurs (IGFDC) dans la perspective de sa relation avec le commandement et contrôle.

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EXECUTIVE SUMMARY

Sensing techniques are employed in military systems as the primary means to gain knowledge about the external environment, or to update and refine such knowledge. In the maritime context, the graphic and textual depiction of any information that may affect the Commanding Officer's decision making in an area of interest is called the Recognised Maritime Picture (RMP). More precisely, the term Maritime Tactical Picture (MTP) is typically used for a Tactical Coordination Center (TCC) afloat. Tactical commanders at all levels require a MTP of their battle space, and most of the information required to compile this MTP comes from sensing sources.

Typically, as a result of their intrinsic shortcomings, single sensor systems have limited capabilities for resolving ambiguities and providing consistent descriptions of the sensed environment. Despite advances in sensor technologies and the myriad computational methods and algorithms aimed at extracting as much information as possible from a given sensor, the irrefutable fact remains; no single sensor is capable of cost effectively obtaining all the required information, reliably at all times, in different and sometimes dynamic environments. Intelligent military systems thus make use of multiple sensors in order to satisfy the extensive need for precise and timely information. Multi-sensor systems aim to overcome the shortcomings of single sensors by employing redundancy and diversity.

For multi-sensor systems, the notion of sensor synergy is very important. It can be described as the organization, coordination and management of sensors, and the combination of the information they provide, such that their overall operation is complementary and non-conflicting given the operational sensing needs. These are the fundamental issues which sensor integration, management and data fusion (SIMDF) address to support situation and threat assessment for military systems, and consequent weapon systems actions. The appropriate integration and management of several sensors, and the intelligent use of the resulting optimum data sets through data fusion, should provide an efficient and operationally valuable approach for military systems.

The aim of this document is to present a framework for addressing SIMDF in the perspective of its relationship to command and control (C2). Issues are raised related to conflict management in the optimization of the various levels of the combat system decision tree organized as C2 and warfare areas. A set of integration rules required for any low level integration to be in line with the decisions made at higher levels is provided. The Defence Research Establishment Valcartier (DREV) has been working for over a decade to develop the technologies to enable Canada's warships to dynamically and automatically obtain an image of the tactical situation and assess the situation in order to protect the ship. R&D activities have been initiated years ago at DREV to explore SIMDF concepts that could apply to the current Above Water Warfare (AWW) sensor suite of the HALIFAX class ships, as well as its possible future upgrades, in order to improve its performance against the anticipated future threat. The scope of this research is within the time frame of the HALIFAX class mid-life refit, and the spin-offs will also be of direct benefit to the IROQUOIS class and its potential replacement.

LIST OF ACRONYMS

AAW	Anti Air Warfare
AI	Artificial Intelligence
ASW	Anti Submarine Warfare
ASuW	Anti Surface Warfare
AWW	Above Water Warfare
C^2	Command and Control
C3I	Command, Control, Communications and Intelligence
CCIS	Command and Control Information System
CCS	Command and Control System
CPF	Canadian Patrol Frigate
CRDV	Centre de recherches pour la défense, Valcartier
DF	Data Fusion
DFRM	Data Fusion and Resource Management
DFS	Data Fusion Subpanel
DoD	Department of Defense (U.S.)
DREV	Defence Research Establishment Valcartier
EMCON	Emission Control
ESM	Electronic Support Measure
GPS	Global Positioning System
IFF	Identification Friend or Foe
IGFDC	Intégration, gestion et fusion des données de capteurs
INS	Inertial Navigation System
IR	Infrared
IRST	Infrared Search and Track
ISS	Integrated Sensor Suite
ISTDS	Internal System Track Data Store

LIST OF ACRONYMS (cont'd)

JDL	Joint Directors of Laboratories
MC3IWAWG	Maritime C3I Way Ahead Working Group
MHT	Multiple Hypothesis Tracking
MSDF	Multi-Source Data Fusion
MTP	Maritime Tactical Picture
OODA	Observe, Orient, Decide and Act
R&D	Research and Development
RM	Resource Management
RMP	Recognized Maritime Picture
SA	Situation Assessment
SIMDF	Sensor Integration, Management and Data Fusion
SM	Sensor Management
STA	Situation and Threat Assessment
TA	Threat Assessment
TCC	Tactical Coordination Center

1.0 INTRODUCTION

As a pre-requisite to carrying out their functions, sensing techniques are employed in military systems as the primary means to gain knowledge about the external environment and the systems' relation to that environment, or to update and refine such knowledge.

Typically, as a result of their intrinsic shortcomings, single sensor systems have limited capabilities for resolving ambiguities and providing consistent descriptions of the sensed environment. Despite advances in sensor technologies and the myriad computational methods and algorithms aimed at extracting as much information as possible from a given sensor, the irrefutable fact remains; no single sensor is capable of obtaining all the required information reliably, at all times, in different and sometimes dynamic environments (Ref. 1).

Motivated by biological organisms, which in essence are multi-sensory perception systems, intelligent military systems could make use of a multiplicity of sensors in order to satisfy the extensive need for precise and timely information by extracting as much information as possible about a sensed environment. Multi-sensor systems aim to overcome the shortcomings of single sensors by employing redundancy, diversity and complementarity.

For multi-sensor systems, the notion of sensor synergy is very important. Sensor synergy can be described as the organization, coordination and management of sensors, and the combination of the information they provide, such that their overall operation is complementary and non-conflicting given the sensing needs of the military system. These are the fundamental issues which sensor integration, management and data fusion (SIMDF) addresses to support situation and threat assessment for military systems, and consequent weapon systems actions.

The appropriate integration and management of several sensors, and the intelligent use of the resulting optimum data sets through data fusion, should provide an efficient and operationally valuable approach for military systems. Suitable use of sensors should provide benefits, including earliest possible target detection, reliable target identification, countermeasure robustness, etc.

The aim of this document is to present a framework for addressing sensor integration, management and data fusion, i.e., the three distinct aspects of the coordinated use of sensor assets to support naval operations, in the perspective of their relationship to Command and Control (C^2). In particular, the document has been written to:

- help establish the terminology regarding SIMDF,
- educate the potential military users of sensing systems by presenting the main concepts from a practical perspective, making minimum use of equations and tedious derivations, and,
- provide a high-level introduction document to the students in universities, and other personnel, that could be recruited to perform research activities in the field of SIMDF.

The document is organized as follows. Chapter 2.0 provides a brief discussion about the use of sensing techniques to tackle the problem of perception in military systems. Chapter 3.0 discusses Multi-Sensor Data Fusion (MSDF) in the context of the overall Data Fusion (DF) domain. The data fusion hierarchy is described, where each succeeding level of processing deals with a higher level of abstraction.

The question of how to best manage, coordinate and organize the use of sensing resources in a multi-sensor system in a manner that improves the process of data fusion synergistically, and ultimately that of perception, defines the sensor management problem discussed in Chap. 4.0.

Finally, sensor integration, a complementary concept to sensor management and data fusion, is briefly described in Chap. 5.0. It is essentially concerned with two main aspects: the maximization of each individual sensor output through synergistic cooperative work with the other members of the sensor suite, and, combat system management to avoid (or at least minimize) inadvertent interference of one sensor system by another.

Just as any other concepts, sensor integration and management have their difficulties. For example, one approach might be appropriate for only specific tasks. But what about the potential conflicts with other goals that a warship's commander has to achieve in order to fulfill his mission? Integration at a lower level than the Command and Control Information System (CCIS) should only be done if it does not interfere with a higher level goal or if the CCIS can manage the interference, e.g., tolerate a small interference for a long period of time or perhaps a high interference for a very short period of time. The CCIS may issue requests that require an adaptive and non-conflicting level of integration when making tradeoffs in servicing multiple goals.

Chapter 6.0 introduces some concepts related to shipboard command and control information systems and the warfare areas (i.e., Anti Air Warfare (AAW), Anti Surface Warfare (ASuW), etc.). Then, Chap. 6.0 raises issues related to conflict management in the optimization of the various levels of the shipboard combat system decision tree organized as CCIS and warfare areas. The tentative definition of a set of integration rules or guidelines required for any low level integration to be in line with the decisions made at higher levels is provided. At last, the main conclusions are summarized in Chap. 7.0, while references are provided in Chap. 8.0.

The research and development activities leading to this document were performed at DREV between January and April 1998 under work units 1ba12 (Investigations of MDSF/STA/RM Concepts) and 1ba18 (Sensor Fusion Concepts Demonstration for CPF Upgrade).

2.0 SENSING IN MILITARY SYSTEMS

As a pre-requisite to carrying out their functions, autonomous military systems must gain knowledge about their environment in order to make inferences about themselves in relation to that environment. For example, naval defence operations afloat typically involve detecting the presence of an unknown number of objects of interest (generally referred to as "targets"), some of which may be hostile, some friendly and some neutral, and estimating their position, motion and identity. Accurately locating and identifying potential targets is indeed a fundamental prerequisite to derive an appropriate response based on available resources and perceived threats.

In mammals, sensory perception provides a way of satisfying the need for knowledge concerning the external environment. Sensory perception can be defined broadly as the process of acquiring information related to the state of nature, thereby obtaining and maintaining an internal description of the external world (Ref. 1).

Similarly, while a military system may have some *a priori* knowledge about its environment, sensing techniques are employed extensively in military applications as the primary means to tackle the problem of perception by providing knowledge about the external environment, and the system's relation to that environment, or to update and refine such knowledge.

This makes the acquisition and refinement of information, the main goal of sensor systems.

2.1 Single-Sensor Systems

Sensors exploit physical phenomena to measure quantities. The measured quantities are expected to provide information about the state of nature. In this case, the state of nature refers to whatever quantities, parameters or variables are of perceptual interest to the military system. It may be a description of the spatial location of an object, its identity in terms of attributes, a complex dynamic state or simply a single numeric quantity. A particular sensor device is considered appropriate for a sensing task when a relationship or mapping exists between the measured quantity and the state of nature (Ref. 1). The exactitude with which this relationship is known depends on how well understood the measurement is, in as far as it relates to the state.

In this regard, physical descriptions of sensors are invariably useful. However, such descriptions or physical models are unavoidably only approximations owing to our lack of complete understanding of the principles governing the transducer operation and consequently the resulting measurement. This is often exacerbated by incomplete knowledge and understanding of the environment and its interaction with the sensor. In addition, sensor measurements inherently incorporate varying degrees of uncertainty and are, occasionally, spurious and incorrect. This, coupled with the practical reality of occasional sensor failure greatly compromises reliability and reduces confidence in sensor measurements. Also, the spatial and physical limitations of sensor devices often mean that only partial information can be provided by a single sensor.

As a result of these shortcomings, a single sensor has limited capabilities for resolving ambiguities and providing consistent descriptions of the sensed environment. And so, despite advances in sensor technologies and the myriad computational methods and algorithms aimed at extracting as much information as possible from a given sensor, the irrefutable fact remains; no single sensor is capable of obtaining all the required information reliably, at all times, in different and sometimes dynamic environments (Ref. 1).

Moreover, most of the sensor (and weapon) systems seriously considered for acquisition over the next 5-10 years have been "sold" on the principle of keeping the ships competitive with the threat which will exist in that time frame. The increasing refinement of modern armed forces with fast and highly maneuverable airborne vehicles leads to a peculiarly dynamic situation on the battlefield, especially in the high risk threat situations experienced by ships in the highest threat areas in time of crisis. Typically, as a worst case scenario, a supersonic sea skimming threat has been defined for the future systems. This means that decision and reaction times are reduced to a minimum, if not beyond. In turn, this means that to maintain an acceptable probability of surviving an attack one will have to detect, classify, track and engage the future threat as far out from the ship as physically possible.

To meet this challenge, relying on a single stand alone data supplier system is in general prohibitively expensive since sensors potentially capable of meeting such operational scenarios, and their associated threats, are complex and very costly as stand alone, autonomous equipment.

2.2 Multi-Sensor Systems

It is thus clear that the sensing functionality needed in complex military systems could exceed the repertoire of any single sensor. Motivated by biological organisms, which in essence are multi-sensory perception systems, intelligent military systems could make use of a multiplicity of sensors in order to satisfy the extensive need for precise and timely information by extracting as much information as possible about a sensed environment. Indeed, the idea of using a set of more or less dissimilar sensors (each sensor providing an amount of information that only partially overlaps with information from other sensors) to collect information related to the properties (kinematics and identity) of a wide variety of potential threats is often deemed critical to the survivability of high-priority military assets.

Multi-sensor systems aim to overcome the shortcomings of single sensors by employing (Ref. 1):

- **Redundancy.** Redundancy is the use of two or more sensors to measure the same or overlapping quantities or spaces. It is well known that redundancy reduces uncertainty. This can be appreciated from the fact that for two sensors, the signal relating to the measured quantity is correlated, whereas the uncertainty associated with each sensor tends to be uncorrelated. Also, redundancy is desirable if sensor failure is anticipated so that system performance is degraded gracefully.

- **Diversity and Complementarity.** Physical sensor diversity is based on the use of different sensor technologies together. Spatial diversity offers differing viewpoints of the sensed environment simply by having sensors in different locations. Such diversity is extremely useful in efforts to reduce uncertainty and is invaluable in resolving ambiguities. Complementarity results if the sensor suite is made up of sensors each of which observes a subset of the environment state space, such that the union of these subsets makes up the whole environment state space which is of perceptual interest to the military system.

By providing measurement data, a sensor can be viewed abstractly as an information source. In a multi-sensor system several such information sources are available, thus making it possible to implement different strategies for obtaining and combining information (Ref. 1). The theory and application of multi-sensor systems is thus determined and defined by the approaches adopted in order to address the following fundamental issues:

- How can the diverse, often incomplete and sometimes conflicting information provided by a variety of sensors in a multi-sensor system be combined in a consistent and coherent manner, and the requisite states or perceptual information inferred?

- How can such systems be optimally configured, utilized and coordinated in order to provide, in the best possible manner, the required information in often dynamic environments?

For multi-sensor systems, the notion of sensor synergy is very important. Sensor synergy can be described as the organization, coordination and management of sensors and the combination of the information they provide such that their overall operation is complementary and non-conflicting given the sensing needs of the military system. These are the fundamental issues which sensor integration, management and data fusion addresses to support situation and threat assessment for military systems, and consequent weapon systems actions. Figure 1 shows the high-level relationship between these three distinct concepts.

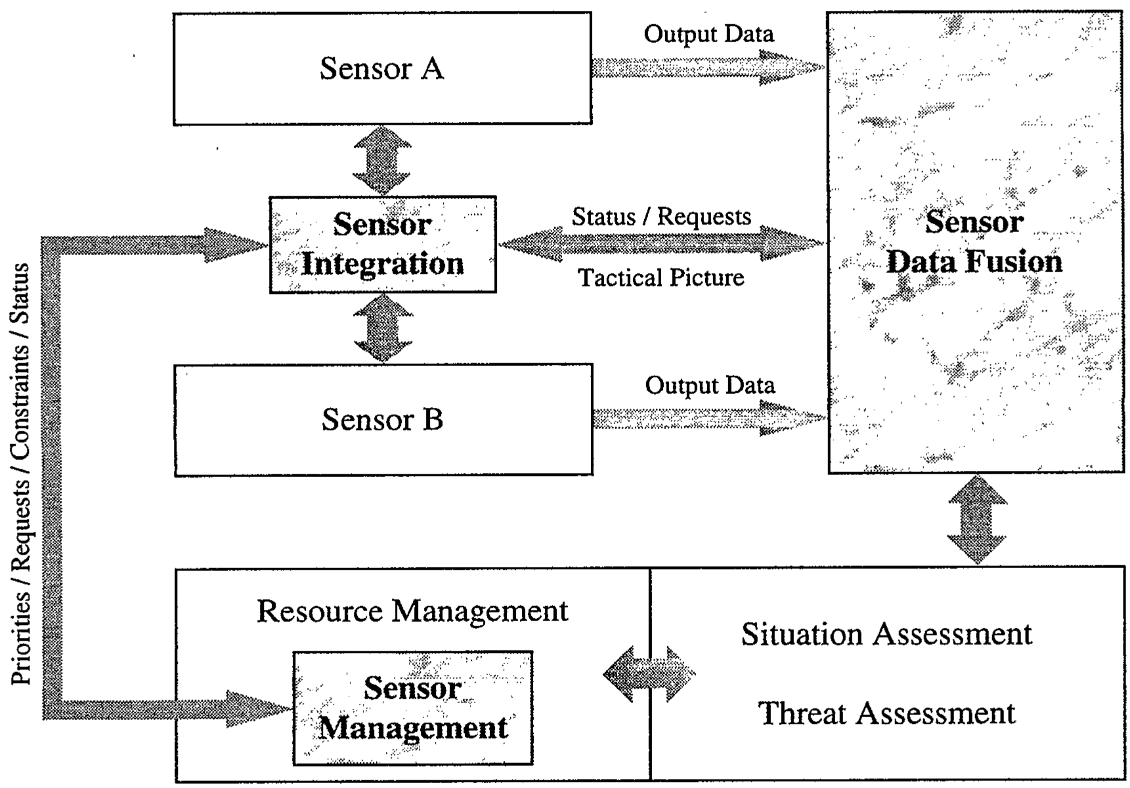

FIGURE 1 - Relationship between sensor integration, management and data fusion

In a military operational environment, the problem is often not one of a shortage of information, but rather one of making sense of diverse and vast amounts of it, or, of recognizing that which is relevant and useful (Ref. 1). Hence, even if the use of multiple sensors appears reasonable and promising, data overload is likely to be as difficult a problem as data deficiency in battlefield conditions. Fortunately, research is progressing well to understand and overcome the problems of fusing data from multiple sensors (Refs. 1-8). Sensor data fusion refers to any stage in the integration process where there is an actual combination (or fusion) of different sources of sensory information into one representational format.

But the maximum operational performance is typically not achieved through sensor fusion alone. Passively accepting data from sensors and attempting to extract maximum benefit through data fusion may not be the optimum procedure. It is generally believed that even more can be gained by integrating and managing two or more sensors as, effectively, a single multi-spectral and multi-spatial sensor, thereby actively controlling the multi-sensor input to provide the best data for a given task.

To illustrate this alternative approach, consider the human sensor suite. Sitting, unmoving and staring ahead with full concentration on all inputs would not be the optimum use of human senses. Appropriate placement of the best combination of dissimilar sensors would be much better. Concentrating on the best subset of senses in a given situation, calling on friends to help and being flexible and proactive would all improve performance and increase efficiency.

It is thus postulated that adaptable and proactive use of multiple sensors, very loosely following the above analogy, would provide similar gains on the battlefield by enabling cost effective optimization of sensor system effectiveness to match the overall sensor combination requirements. With respect to integration, the linkage of two or more sub-optimal systems with compatible communications may provide the redundancy and performance needed. Some studies indicate, for example, that the probability of early detection, classification and tracking by a radar system is considerably improved when the radar data are correlated with that of an IR sensor. Similar synergy for other systems may exist. With the management of the sensors it may be possible to optimize the spatial, temporal and wavelength of the sensors used to meet the particular sensor requirements against the threat of the moment.

In summary, the appropriate integration and management of several sensors, and the intelligent use of the resulting optimum data sets through data fusion, should provide an efficient and operationally valuable approach for military systems. Suitable use of sensors should provide benefits, including the followings (not in any particular order):

- earliest possible target detection,
- reliable target identification,
- more efficient prioritization and hand over to track,
- accurate target track for engagement,
- better matching of sensors (to climatic/meteorological conditions; target types/signatures; clutter conditions; false alarm rates; resolution requirements),
- countermeasure robustness,
- more confidence in target parameters,
- optimization of time lines,
- covertness/survivability, and,
- graceful degradation.

Sensor integration, management and data fusion are discussed in more details in the next chapters.

3.0 DATA FUSION

Clearly, what data fusion encompasses depends on how it is defined (Ref. 1). In a literal sense, *data* refers to the actual measurements taken or information obtained by the sensors and other sources, and *fusion* is the process of combining this data or information in such a way that the result provides more information than the sum of the individual parts.

Throughout the 1980s, the three U.S. military services pursued the development of tactical and strategic surveillance systems employing data fusion and supported extensive research in the areas of target tracking, target identification, algorithm development for correlation (association) and classification, and the application of intelligent systems to situation assessment (Refs. 2-7). The large amount of fusion-related work in this period raised some concern over possible duplication of effort. As a result, the Joint Directors of U.S. Department of Defense (DoD) Laboratories (JDL) convened a Data Fusion Sub-panel (DFS) to (1) survey the activities across all services, (2) establish a forum for the exchange of research and technology, and (3) develop models, terminology and a taxonomy of the areas of research, development and operational systems. As a result of many years of effort to establish standardization and stability in the lexicon of data fusion, the definition of many terms has slowly achieved consensus across the diversified application community. Problem-specific nuances and shading in these definitions remain but agreement on a meaningful subset of terms does seem to exist.

Data Fusion is an adaptive information process that continuously transforms the available data and information, obtained from a variety of sources, into richer information through the continuous refinement of hypotheses or inferences about real-world events. The sources of information may be quite diverse, including sensor observations, data regarding capability and availability of targets, topographic and environmental data, and information regarding doctrine and policy. The objective is to achieve refined (and potentially optimal) estimates of the kinematics and identity of individual objects, and to derive complete and timely assessments of current and future situations and threats and their significance in the context of operational settings. The process is also characterized by continuous refinements of its estimates and assessments, through the evaluation of the need for additional data and information from the sources and/or the modification of the process itself, to achieve improved results.

3.1 Data Fusion Hierarchy

The process of data fusion may be viewed as a multi-level, hierarchical inference process whose ultimate goal is to assess a mission situation and localize, identify and analyze threats. However, not every data fusion application is responsible for all of these outputs. Some applications are only concerned with the kinematic properties and identification of objects. Others are primarily oriented to the situation and how it is evolving. Still others focus on the threat and its possible impact on achieving mission objectives. In addition, data fusion can be responsible for identifying what information is most needed to enhance its products and what sources are most likely to deliver this information.

Given these considerations, a complete data fusion system can typically be decomposed into four levels (Refs. 2-7):

level 1 - object refinement through multi-source data fusion (MSDF),

level 2 - situation assessment (SA),

level 3 - threat assessment (TA), and,

level 4 - process refinement through Sensor Management (SM).

Each succeeding level of data fusion processing deals with a higher level of abstraction. Level 1 data fusion uses mostly numerical, statistical analysis methods, while levels 2, 3 and 4 data fusion use mostly symbolic, artificial intelligence (AI) methods. A fifth level, i.e., source preprocessing at level 0, is also sometime considered for sensor signal data refinement.

3.2 Level 1 – Object Refinement (Multi-Sensor Data Fusion)

Multi-Sensor Data Fusion (MSDF) is about tactical picture compilation (Ref. 8). In the typical scenarios we are interested in, there can be anywhere from a few to hundreds of targets to monitor. MSDF is concerned solely with individual entities (helicopters, aircraft, missiles, etc.) considered in isolation (i.e., groups or formations of entities are not considered at this fusion level).

An MSDF system processes the information data reported by multiple dissimilar sources in order to correctly and quickly derive the best estimates of the current and future kinematic properties for each hypothesized (or perceived) entity in the operational environment, and to develop inferences as to the identity and key attributes of these entities.

The MSDF system attempts to acquire and maintain unambiguous, stable tracks corresponding to the perceived population of real objects within the operational volume of interest (i.e., establish a number of clean tracks that corresponds exactly to the number of objects in the physical environment). The system also attempts to suppress unwanted objects (i.e., reject residual false returns from noise, clutter, interference, and jamming to discard "uninteresting" targets from the scene). In practice, it is important that the MSDF system strikes a balance between too many (false) and too few (faint but real) targets.

Required are methods for combining diverse information in a manner that is consistent, coherent and avoids distortion or biases caused by malfunctioning sensors or outlier (rogue) measurements (Ref. 1). Having combined all the available relevant information, we need to infer the state of nature in a manner that is optimal by some criteria, given the inherent uncertainty in sensor measurements. Figure 2 shows a generic

MSDF system where the key functions are identified (Ref. 8). The processing can be divided into blocks such as:

- internal system track data store (ISTDS),
- input data preparation,
- system track selection,
- data alignment,
- data association,
- cluster management,
- kinematics data fusion,
- identity data fusion,
- track management, and,
- configuration monitoring and control.

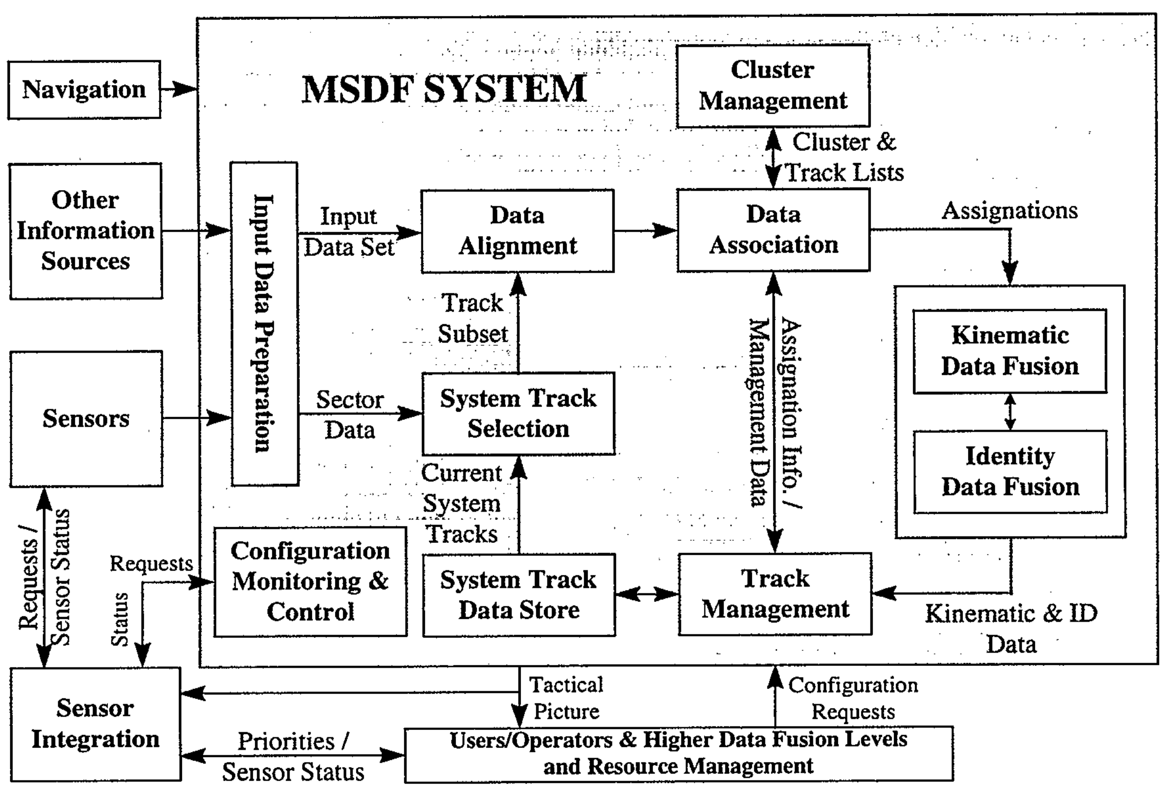

FIGURE 2 - Generic Multi-Source Data Fusion (MSDF) system

These blocks operate in a well-orchestrated manner to map the source data onto the internal system track data store (ISTDS).

During its operation, the MSDF system generates an estimated tactical picture that should accurately reproduce the ground truth tactical picture. This perception of truth by the MSDF system is embodied in the tracks that are established and maintained as the information sources sample the environment. The ISTDS contains the resulting track data obtained after each new sensor or link report has been processed and fused (i.e., the sequence of updates of the kinematic and identity information maintained for each track). Typically, each track record in the ISTDS includes a state vector (with a corresponding covariance matrix) estimating the target kinematic properties, and one or more propositions about non-kinematic properties of the target, each with its associated likelihood function. The information kept in a track record can also include a time tag corresponding to the last update time, the quality of the track, the blip/scan parameter for each sensor, etc.

To achieve its objective, the MSDF system uses, in real-time, the information provided by all of the input channels. These channels supply real-time data such as that generated locally by the own-ship's active and passive sensors and that received from other platforms via communication data links. Hence, contacts (or raw measurements) and tracks from multiple dissimilar sources are processed to form the tactical picture in the local area surrounding the military system. Typically, autonomous modern sensors process their own raw data to produce sensor-level tracks. However, depending on the selected fusion architecture, it is assumed that one also has access to the raw sensor reports.

One can think of the first set of tasks to be performed by the MSDF system as a data preparation process. This process is crucial for the subsequent processing activities performed by the MSDF system. The input data preparation function implements the various interface and buffering mechanisms necessary to adequately receive the contact and track data from the sources. Some data alignment activities are performed on the input reports and the grouping task creates input data sets for the subsequent processing functions either by grouping these input reports in spatial regions, time intervals or just by their absolute time tag. Finally, the input data preparation function provides a source input data control capability to control false alarms and prevent system saturation.

When new data are received from the information sources, a pre-selection of the system tracks that could potentially be associated to the input data set elements is performed. The purpose of this step is to minimize the amount of data to be submitted to the data association algorithm. As a result, the processing time of the latter should be greatly reduced.

Each source typically provides positional data with respect to its own coordinate system and time frame. Hence, in any MSDF system, data alignment in time and space must take place before data association and fusion can be performed. Moreover, in order to estimate and remove the effects of ownship motion from the data, various Inertial Navigation Systems (INS) are used, involving a wide variety of motion sensors including gyroscopes, accelerometers, and the Global Positioning System (GPS) (Ref. 9). The motion corrected data are subsequently processed to form and maintain tracks.

The fundamental problem in a multi-sensor multi-target scenario lies in resolving the ambiguous data association decisions. For the reasons given below, it is difficult, when tracking multiple targets in a cluttered environment, to select the correct or true return from a given target among many returns. As a result, an input data element that is used for track updating might not have originated from the target of interest, but instead may be due to clutter. Hence, although one may know how to perform optimal data fusion, one must first select the correct input data element to be used within the fusion function for track updating.

The data association process has to deal with three causes of input data uncertainties:

- uncertainty related to source data availability (e.g., the probability of detection for a given target is generally less than one; consequently, a sensor measurement originating from this target is not always available);
- uncertainty related to source data resolution and accuracy (if the observations provided by the sources were perfectly accurate, there would be no correlation problem);
- uncertainty related to the origin of the input data elements (i.e., the presence of clutter and sensor receiver thermal noise give rise to false alarms).

The first two causes are a consequence of the technological limitation of any measurement device and the physical properties of the target-sensor environment. The third one comes from external effects which do not originate from the target of interest.

Cluster management is about partitioning the entire set of system tracks and input data elements into separate clusters for the purpose of forming data association hypotheses (Ref. 10). A cluster is completely defined by specifying the set of system tracks and input data elements contained in the cluster, and the alternative data association hypotheses which relates these tracks and input data. System tracks within each cluster share common input data elements, whereas system tracks in different clusters do not share any common input data. A great deal of simplification may result from forming such clusters. A large tracking problem is divided into a number of smaller ones that can be solved independently. That is, one can form data association hypotheses and select the most likely assignment independently for each cluster. Consequently, the combinatorial problem associated with forming hypotheses is reduced significantly. An obvious advantage of clustering is the ability to parallelize the computations.

MSDF refers to the process of amalgamating multiple-source data sets while providing relevant target estimates based on all this information. Such a scenario arises when considering multiple sources providing information pertaining to the same physical entity (i.e., redundant observation). The data fusion process is responsible for the combination of the correlated source data coming from the data association process discussed above. Much work has been done in developing methods of combining information from different sensors. In general, the basic approach has been to pool the information using what are essentially "weighted averaging" techniques of varying degrees of complexity (Ref. 1).

The kinematics information fusion process uses a variety of algorithms and techniques to merge the information content of each of the assigned input data elements with that of the corresponding system tracks. The process automatically weights the influence of each input element based on the current system track accuracy, the perceived accuracy of the input element, and the preprogrammed specification requirements. These requirements typically allow for a trade-off of maneuvering target track continuity, process lag, accuracy, etc.

The target identification aspect also needs to be considered in order to produce the complete tactical picture required by the subsequent, higher-level data fusion processes (Refs. 11-14). The identity data fusion function must accurately integrate the distinguishing attributes of the targets actually observed, and provide estimates of their identification.

In a multiple-target environment, where an unknown number of targets are entering the surveillance volume at any time while some others are leaving this same volume or are destroyed (we also include here the random false alarms and the clutter), there is an evident requirement for a track management process. Indeed, the elements of initial track formation (birth), track maintenance (life), and track deletion (death) are common to all versions of the multiple-target tracking system. Track status is typically defined in terms of four stages of track life: potential, tentative, confirmed (or firm), and deleted, corresponding to the processes of track initiation, confirmation and deletion.

Tracks must be initiated as new targets enter the surveillance region of the sensors. The implications of failing to initiate a track on an emerging target can be catastrophic. Once a tentative track has been initiated, a metric to discern its quality is constructed and monitored. If this measure exceeds a predetermined threshold the track is said to be confirmed, resulting in an increase in the number of perceived targets by the MSDF system. As is often the case, one or more of the system tracks being maintained by the MSDF system may cease to exist. This may be the result of the target leaving the system coverage area, the target threat being removed, or simply due to a loss of the track. Such a system track that is not updated becomes degraded and is considered to be an unreliable or inconsistent estimate of the target it represents; it must therefore be deleted. This fourth and final stage of the track life should result in the track being removed from the system track data store.

As previously mentioned, the output of the MSDF system (i.e., a highly reliable computation of the tactical picture) is used as an input to the subsequent (higher level) data fusion processes. The users/operators of the MSDF system can also interact with it to request amplification data or to participate in the track management process. Indeed, the overall MSDF system is typically not operating in an open loop manner; it runs under the supervision of the configuration monitoring and control function shown in Fig. 2. In order to refine the MSDF process by maintaining the best system configuration as dictated by the current situation, this function outputs MSDF status information and accepts data/requests from components external to MSDF (e.g., users/operators, sensor integration, higher level data fusion processes, etc.).

MSDF configuration monitoring and control comprises many aspects:

- system initialization,

- system capacity overload,
- environmental conditions,
- status of various shipboard systems, and
- MSDF process refinement through resource management.

The MSDF system must accept the MSDF configuration data that allow the various MSDF functions and sub-functions to configure themselves at initialization, prior to any operation. These configuration data could include for example the maximum number of hypotheses to be kept by a Multiple Hypothesis Tracking (MHT) algorithm for each input data set cycle, the assumed process noise values of the target model to be used by an adaptive Kalman filter, etc.

Given that the MSDF system has to perform in real-time (i.e., the system has to meet severe real-time constraints imposed by the system environment), it would be appropriate to include in the set of system capabilities a capacity monitoring process. This process could be called periodically and be responsible for maintaining such things as track counts for the various track status groups (i.e., potential, tentative, firm, lost), track types (air, surface, etc.), etc. Since these counts could provide the operators with information to assess and dynamically adjust system performance, they could be sent periodically to the users through the appropriate interface. In that respect, the monitoring process could also be responsible for issuing and clearing various MSDF system alerts (such as track data store capacity alerts, etc.).

The configuration monitoring and control function must keep track of the environmental conditions since, for example, the rain state and the sea state are good indicators of the detection capability of the radar and IFF sensors. The function also has to maintain the navigation, sensors and communication link status in such a way that MSDF is aware of any change in the ship configuration or any change in the relations among the MSDF parameters and the military system configuration.

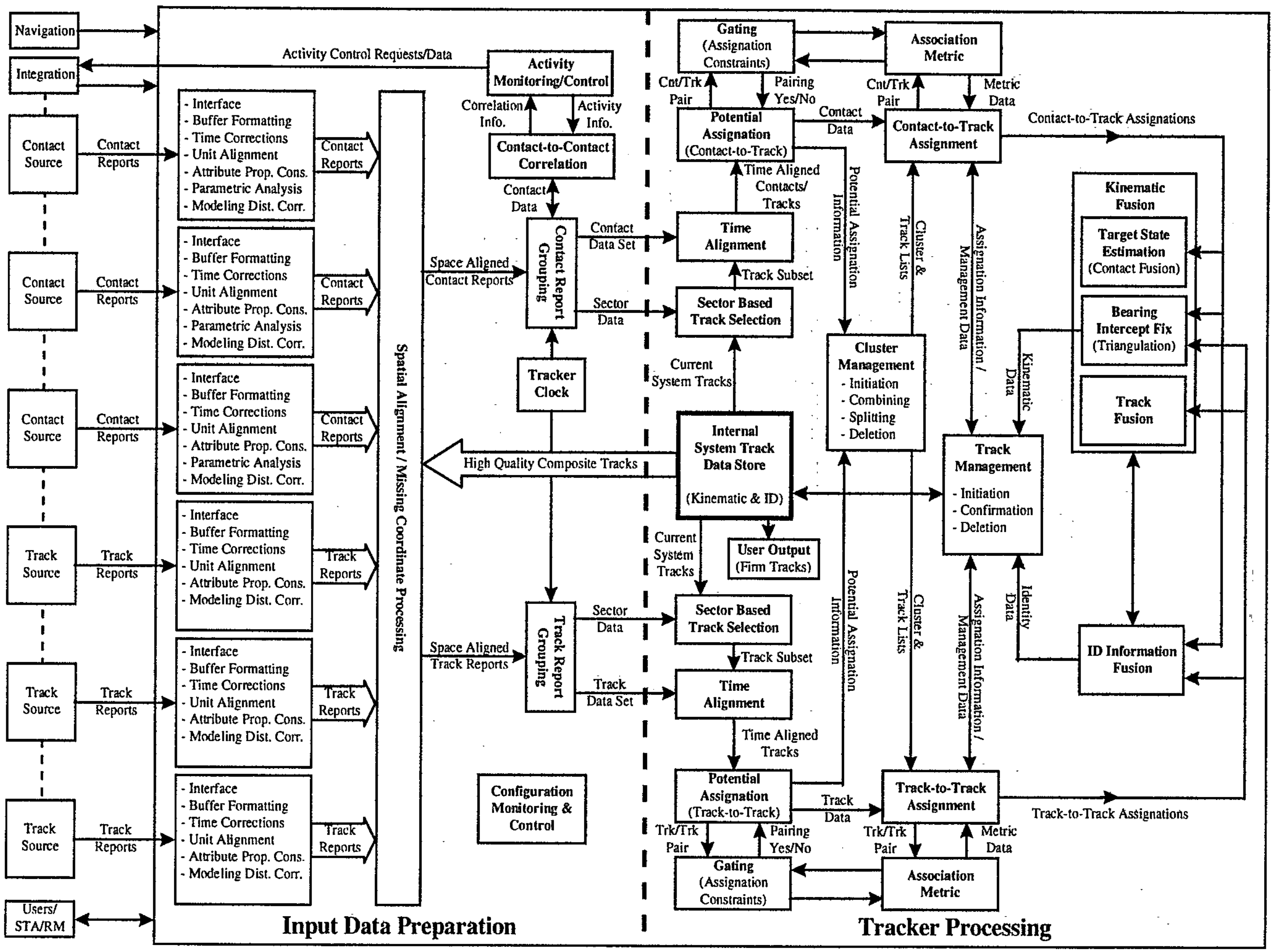

FIGURE 3 - Detailed functional decomposition of a generic MSDF system

Figure 3 shows a detailed functional decomposition of the generic MSDF system discussed above. A complete description of this system is given in Ref. 8.

3.2.1 MSDF Architecture

For any given sensor suite configuration, there can be many different ways to combine data from the sensors. The term "MSDF architecture" is used to indicate the general method (or philosophy) used to combine the sensor data into global tracks (Ref. 15). Hence, a fundamental conceptual issue in developing an MSDF system for surveillance and tracking purpose is the selection of an appropriate architecture. This issue revolves about defining where to combine or fuse the data in the processing flow of multiple sensors, or equivalently the level of preprocessing of the information data which is fused. The MSDF architecture is an important issue since the benefits of the fusion process are different depending on the way the sensor data are combined. The selection of the appropriate MSDF algorithms and techniques also depends on the fusion architecture. Hence, before an MSDF function can be implemented within a military system, it must be analyzed in terms of the different types of architectures and implementations that are possible, the benefits and drawbacks of these architectures, and finally in terms of how all this relates to the performance and mission requirements of the system.

The architecture of an MSDF system can range from highly centralized (or monolithic) to highly distributed. Based on the level at which the sensor data are fused (i.e., signal, contact or track level), Fig. 4 illustrates on a single diagram the usual MSDF architecture possibilities for two generic sensors.

One possible type of MSDF architecture is based on maintaining sensor-level tracks using local sensor information at each sensor site, finding (in a central fusion resource) the sensor tracks that potentially represent the same target and then combining these tracks into global tracks of the MSDF function. This architecture is typically referred to as "Track-Level Fusion", "Autonomous Sensor Fusion" (referring to the fact that each sensor has its own autonomous tracker), or "Sensor-Level Architecture" (referring to the level at which sensor data will first be combined into tracks).

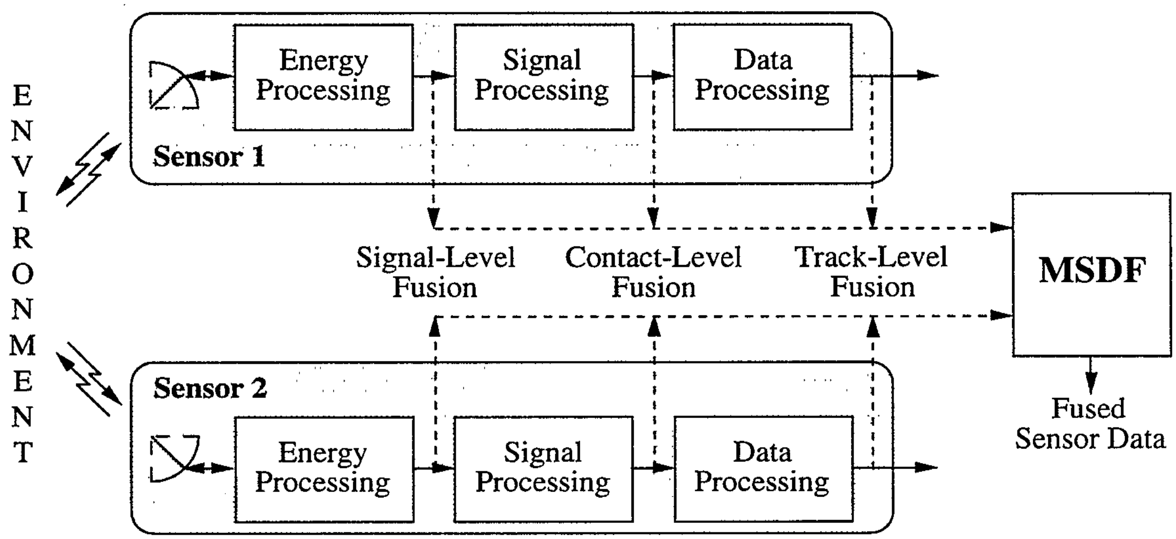

FIGURE 4 - Potential MSDF architecture possibilities for two generic sensors

The primary alternative architecture assumes that all of the raw sensor measurements (i.e., sensor contacts) are sent directly to the centralized MSDF function to be combined into global tracks. This architecture is typically referred to as "Contact-Level Fusion", "Centralized Fusion", or "Central-Level Architecture" since tracks are only formed into the central processor.

The two basic architectural approaches discussed above have predominated most published work. However, as illustrated in Fig. 4, fusion at the signal-level is also possible, combining signals from similar sensors to produce a better quality signal of the same form. In general, this is only feasible between identical sensor devices, all having the same perspective. Trying to fuse representations derived from two imaging sensors at the pixel level is an example involving such an architecture.

Because both the centralized and autonomous sensor fusion architectural options suffer from potential problems, a hybrid approach that permit selective transitions between these two extremes may be appropriate for a particular application. Typically, hybrid architectures allow data reduction prior to fusion as in the autonomous sensor fusion while permitting extraction of raw observations as in the centralized fusion to allow for selective enhancement of target declarations and resolution of ambiguities. Systems have also been proposed that employ a different hybrid approach concept, incorporating both centralized fusion for similar source sensors, and distributed fusion nodes for dissimilar source sensors. There are thus various ways the mixture can be designed, leading to many fusion systems all having different characteristics and performance.

TABLE I

Summary of trade-offs for centralized versus autonomous sensor fusion

BENEFITS OF CONTACT-LEVEL FUSION	BENEFITS OF TRACK-LEVEL FUSION
• Increased Reaction Time - Longer Range at Detection - Quicker Track Initiation / Confirmation / Reporting • High Track Quality (Maximum Available Information) - Optimum Track Accuracy - Good Track Continuity - Low Probability of Miscorrelation • Good False Track Suppression • Algorithms Similar to the Single-Sensor Case	• Low Communication Requirements (Bandwidth) • Low Computational Requirements (In Any Single Processor) • Inherently Benefits from Concurrent Processing • High Survivability (Distributed System) • High Robustness to Sensor Data Degradation • Allows the Design of Sensor-Specific Estimation Processes • Simplified Data Association Problem • Does Not Require Commensurate Sensors • Natural Evolution from Current Multiple-Sensor Systems
DRAWBACKS OF CONTACT-LEVEL FUSION	**DRAWBACKS OF TRACK-LEVEL FUSION**
• High Communication Requirements (Bandwidth) • High Computational Requirements (Central Processor) • High Vulnerability (Centralized System) • Low Robustness to Sensor Data Degradation • Difficult Data Association Problem • Requires Commensurate Sensors • Requires Modifications to the Current Autonomous Sensors	• Poor Reaction Time - Shorter Range at Detection - Late Track Initiation / Confirmation / Reporting • Reduced Track Quality (Loss of Information) - Poor Track Accuracy - Poor Track Continuity - Increased Probability of Miscorrelation • Poor False Track Suppression • Requires Specialized Algorithms (Dependent Tracks)

Qualitative trade-off analyses of the centralized and autonomous sensor fusion architectural approaches are presented in many papers and textbooks. Reference 15 presents a synthesis of these qualitative analyses, and the results of a quantitative comparison of these two architectural options. Each approach has benefits and drawbacks. These are summarized in Table I. As made obvious with Table I, the advantages of centralized fusion are the mirror image of the disadvantages of the autonomous sensor fusion approach, and vice versa.

3.3 Level 2 - Situation Assessment

Based on incomplete and inaccurate sets of data and information, situation assessment (SA) is devoted to the continuous inference of statements about the hypothesized objects provided by the lower level data fusion function in order to derive a coherent, composite recognized picture of the situation. This picture must be described in terms of groups or organizations of objects so that enemy intent can be estimated in the next level and decisions can be made by decision makers about how to use war fighting assets.

SA deals with monitoring and short-term or immediate situation diagnosis. Hence, SA consistently matches hypothesized objects with known and expected organizations and events, while conforming to terrain, enemy tactics and other warfare constraints, to develop a description or interpretation of the current relationships among these objects and events in the context of the operational environment. The result of this processing is a determination or refinement of the battle/operational situation.

Based on the situation abstraction products and information from technical and doctrinal databases, SA also attempts to anticipate future events over a short time horizon.

Key SA functions include: object aggregation, event/activity aggregation, contextual interpretation/fusion and multi-perspective assessment. A description of these functions is provided in Ref. 16.

3.4 Level 3 - Threat Assessment

Threat assessment (TA) is focused at the details necessary for decision makers to reach conclusions about how to position and commit the friendly forces. It can be viewed as a longer term diagnosis function to determine problems in the current situation and identify opportunities for taking corrective actions.

By coupling the products of situation assessment with the information provided by a variety of technical and doctrinal databases, TA develops and interprets a threat oriented perspective of the data to estimate enemy capabilities and lethality, identify threat opportunities in terms of the ability of own force to engage the enemy effectively, estimate enemy intent (i.e., provide indications and warnings of enemy intentions), and determine levels of risk and danger.

Hence, TA uses the recognized situation picture from level 2 and what is known about the enemy doctrine and objectives to predict the strengths and vulnerabilities of the threat forces and friendly forces. In addition, the friendly mission and specific options available to decision makers are tested within these strengths and vulnerabilities to guide decision making.

Key TA functions include: enemy forces capability estimation, prediction of enemy intent, identification of threat opportunities, multi-perspective assessment and offensive/defensive analysis. A description of these functions is provided in Ref. 16.

3.5 Level 4 - Process Refinement (Sensor Management)

With MSDF (i.e., level 1 data fusion) defined as above, an additional matter arises, which is the question of how to best manage, coordinate and organize the use of sensing resources in a multi-sensor system in a manner that improves the process of data fusion, and ultimately that of perception, synergistically (Ref. 1). This defines the sensor management problem discussed in the next chapter.

4.0 SENSOR MANAGEMENT

In the context of level 4 fusion processing, the sensor management (SM) function is mainly concerned with the refinement of the information gathering process. It has the responsibility of closing the Boyd's command and control OODA (Observe, Orient, Decide and Act) loop by first examining and prioritizing what is unknown with respect to the current situation and threat. Then, based on its findings, SM develops options for collecting additional information.

In particular, it is important to manage and coordinate the assignment of sensors to targets (or features) in order to use sensing resources effectively (Ref. 1). This also ensures that all the features that need to be observed are covered in a manner which is consistent with system goals. To be most effective, the management of sensor-feature assignments must take into account the dynamic nature of the problem, such as in the case of moving targets or moving sensor platforms, by continually reviewing current assignments.

Implicit in a sensor management problem is the existence of either several sensing strategies such as those provided by agile or multi-mode sensors, or several alternative configurations for the multi-sensor system. When presented with several sensing options or configurations, the option making the best use of sensor resources to achieve system goals must be chosen. For example, with sensors capable of operating in several modes, it becomes necessary to make decisions concerning the most appropriate mode for a given situation. This is similar to the situation where there are several physically diverse sensors available. In such cases it becomes necessary to manage such diversity, i.e., make decisions regarding the appropriate sensor or sensor mode for a particular observation activity.

Sensor management thus ultimately reduces to making decisions regarding alternate sensing strategies. Sensor management decisions typically result in the following sequence of events:

1. decisions are implemented as sensing actions,
2. as prescribed by these actions, sensor measurements are obtained which are expected to contain information about the state of nature, and
3. from these measurements the state of nature is estimated or inferred, thus furnishing beliefs or knowledge about the environment.

Clearly, the correctness and optimality of the result hinges on the "rationality" of the original decision-making process which prescribes the sensing actions. For this reason, the rationality of the decision-making process is of utmost importance.

The basis for evaluating decisions (or the criteria for management) can be thought of as the management imperative. Implicit is a requirement for an a priori understanding of the perceptual goals of the system. These goals provide a basis for the criteria used to evaluate the efficacy of alternative strategies and configurations. The management imperative can thus be described as the underlying motivating purpose of the sensing system (i.e., the system goal), on which any sensing activities or choices can be based and is an abstraction of more specific sensor functions and task requirements

In general, sensor management has as a proximate goal the optimal management of sensing resources and capabilities in order to gain maximum information and refine knowledge about given states of nature, while minimizing threat to system and assets (e.g., EMCON conditions). In a given sensor system this may be refined to include more specific requirements such as observation and track maintenance, and effective coverage of a target set.

The information update paradigm leads to an intuitive method of addressing sensor management. An intuitive basis for making decisions leading to the best sensing configuration or actions is a consideration of the value of the sensing information obtained. This leads to the development of a method for sensor management which makes use of information metrics as the expected utility.

Once sensor management has developed options for collecting additional information, priorities are eventually sent to a sensor integration function (shown in Figs. 1-3) for the scheduling and cueing of the appropriate sensors and data collection sources. This function, on the basis of an evolving picture and under the supervision of the overall command and control resource management process, controls the information that the MSDF system might receive by pointing, focusing, maneuvering, and adaptively selecting the modalities of the sensors and sensor platforms. The interaction of the sensor integration function and the MSDF system is mainly done through the configuration monitoring and control sub-function previously discussed that is responsible for the initialization of the MSDF system, and the setup and adjustment of the various MSDF algorithm parameters to control the quality of the MSDF product.

5.0 SENSOR INTEGRATION

Sensor integration, a complementary concept to sensor management and data fusion, is essentially concerned with two main aspects:

1. the maximization of each individual sensor output through synergistic cooperative work with the other members of the sensor suite, and

2. combat system management to avoid (or at least minimize) inadvertent interference of one sensor system by another.

With respect to the first issue, sensor integration means that sensor systems talk to one another, or to the command and control system, in order to modify their respective parameters to enhance given functions. By making the multiple sensors interactive and mutually supportive, it allows each individual sensor to do its task better than if used as a stand alone autonomous sensor.

In particular when using sensors with limited fields of view, it is important to ensure that features or targets which may pass out of view are not lost. Hence, it may become necessary to cue sensors into whose field of view a feature may be entering (Ref. 1). Cueing may be done in a cooperative manner, e.g., when sensors capable of obtaining different information cooperate to resolve ambiguity concerning a particular feature. An example could be a radar cueing an IRST to lower its detection threshold in a given sector, thereby locally improving the individual performance of the IRST. The sector has to be sufficiently small in order to keep the probability of false alarm constant, at a reasonable level. Hand-off refers to the transfer of the observation of a feature by one sensor to another. As expected, sensor cueing and hand-off should be consistent with system goals.

Although such cooperative work is very important, the minimization of any system-to-system interference that may potentially result from the intrinsic nature of each sensor system is also essential to the success of a fully integrated military capability. Consider for example a modern radar system with a built in frequency agility feature and an Electronic Support Measure (ESM) system that are collocated on a military platform. Without interference management, it could happen for a brief period that the radar radiates high power in a frequency band where the ESM is currently listening. This would produce catastrophic results. Techniques and procedures are thus required to ensure compatible operation of current and future sensor systems.

In view of the discussion above, total sensor integration requires that each sensor be able to receive and use pertinent information from other sensors, or from the command and control process, in order to improve or refine its own performance and reduce system-to-system interference. Unfortunately, since sensors are being developed as standalone systems as things stand in general, sensor integration in the case of main shipboard sensors may prove to be difficult because there is typically no provision to modify on-line the operating mode or to access the main data processing functions. Usually, the modification of the original sensor design after procurement and installation is not cost effective. As much as possible, new, modern equipment should thus be initially designed with a flexible capability for external control and with an open architecture that allows for an easy integration with other components of the combat system.

6.0 SIMDF AND COMMAND AND CONTROL SYSTEMS

Addressing sensor integration, management and data fusion in decentralized systems presents some added difficulties. For example, reducing interference and optimizing performance in the warfare areas may unfortunately create some conflicts with other goals that a commanding officer has to achieve in order to fulfill his mission. These are due to the potentially autonomous nature of the sensor nodes in the decentralized system. The problems are as follows; (i) how to guarantee consistency and consensus amongst decision-makers, (ii) the nature of the criteria for optimality and the question of group or individual optimality, and not least (iii) the maintenance of coherence and rationality in the decisions made. These are the classic problems encountered in group or decentralized decision theory.

This chapter raises issues related to conflict management in the optimization of the various levels of the combat system decision tree organized as CCIS and warfare areas. The tentative definition of a set of integration rules or guidelines required for any low level integration to be in line with the decisions made at higher levels is provided.

6.1 A Decision Process: The OODA Loop

In support to the discussion of sensor integration interference and conflicts, this section only briefly introduces some of the main concepts of command and control.

The primary functions of the Command and Control Information System (CCIS) afloat (also known as the Tactical Coordination Center (TCC)) is to collect, display, evaluate and disseminate the information necessary for the commanding officer to effectively exercise command and control over an operation for which he is responsible (Ref. 17). Figure 5 depicts the commonly used command and control decision loop, better known as the Boyd's Observe, Orient, Decide and Act (OODA) loop. Figure 5 also illustrates how the four levels of data fusion map onto the CCIS OODA loop.

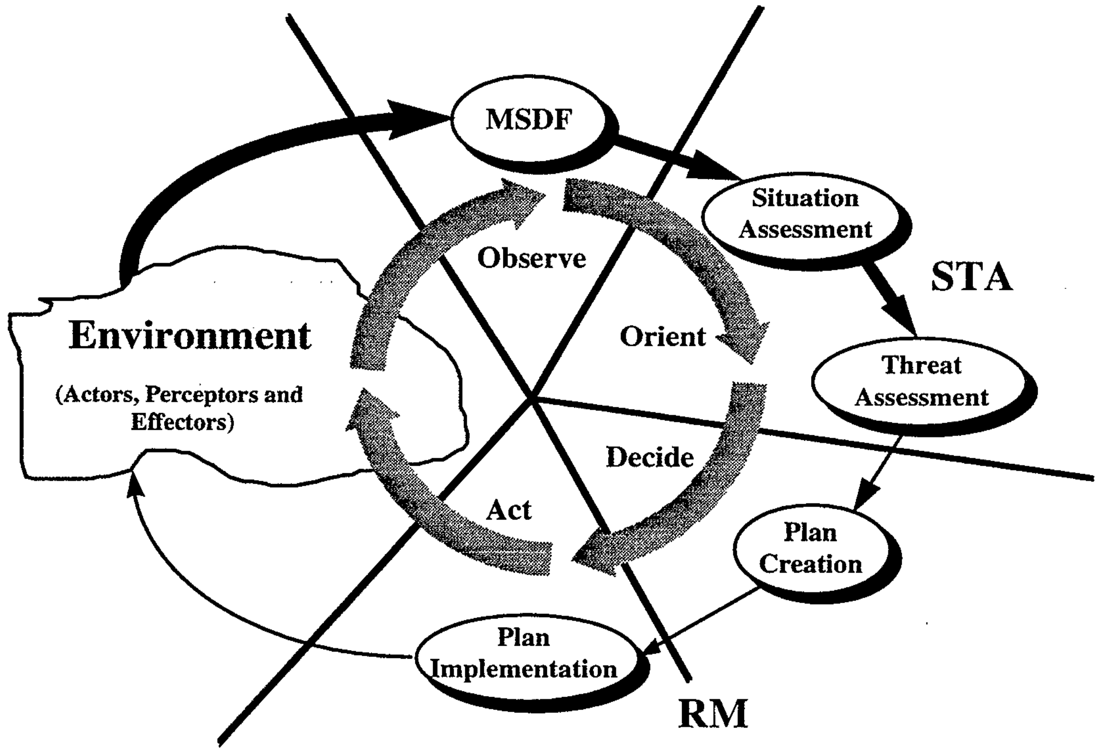

FIGURE 5 - The OODA loop

Situation and threat assessments (STA), together with command team interactions, as required and as response time permits, is used to drive the planning and decision support functions for allocating and scheduling the use of critical defence resources and coordinating response actions in support of the mission. Determination of the various options for use of the resources and the selection of the best course of action in a given situation is known as resource allocation. Resource management (RM) refers to the continuous process of planning, coordinating and directing the use of the ship or force resources to counter the threat. It is therefore concerned with issues of both command and control.

As previously mentioned, resource management in the context of level 4 fusion is mainly concerned with the information gathering process refinement (i.e., sensor management). However, the overall domain of resource management also encompasses the management of weapon systems and other resources. Figure 6 illustrates the overlap between the data fusion and resource management domains.

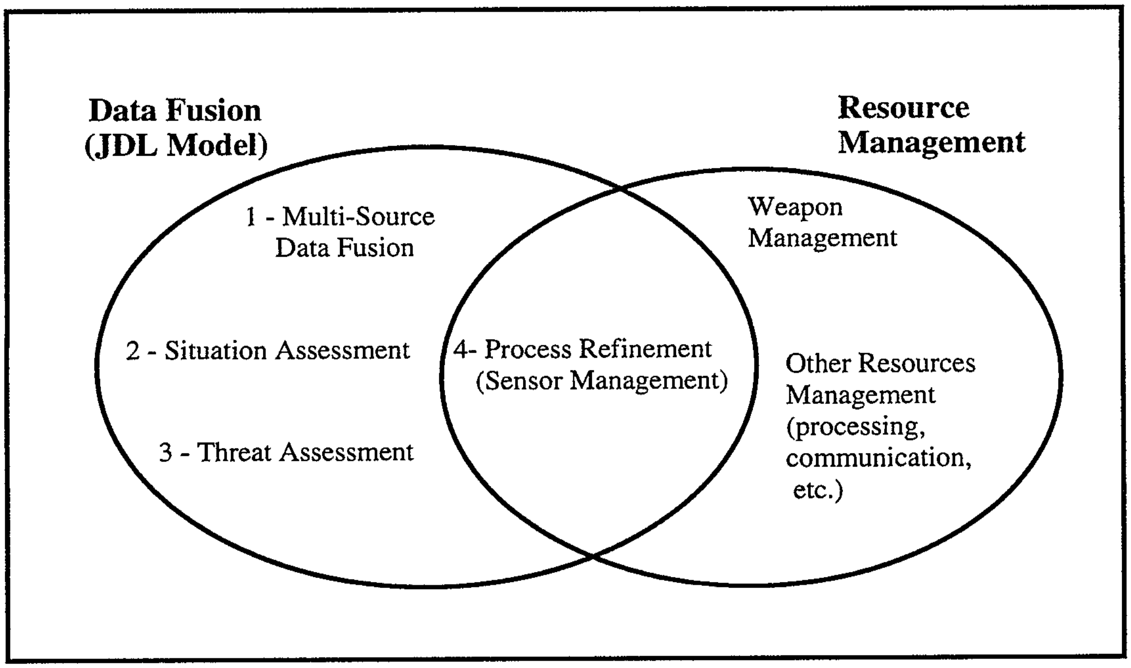

FIGURE 6 - Overlap between the data fusion and resource management domains

As shown in Fig. 5, the CCIS interacts with its environment. This is a very important aspect since the CCIS must keep pace with the outside world. The environment is a complex dynamic system that includes a multiplicity of components. These are the perceptors (i.e., the sensors and other information sources) supporting the observation of the environment, the effectors (e.g., the hardkill/softkill weapons) used to act upon the environment, and the actors. The latter include the friends, the neutrals and, potentially, the foes.

Regarding the external environment, the greatest threat to most warships in the foreseeable future will be from air attacks by sophisticated anti-ship missiles launched from air, surface, subsurface and land-based platforms. Such a threat is extremely difficult to defeat because these missiles are typically very lethal, very fast and stealthy (imposing very short reaction time), and they are frequently launched in waves or salvoes (i.e., multiple simultaneous engagements) in a very complex environment (i.e., a large number of friends, foes, neutrals, etc.).

Countering the anticipated threat clearly demands an extremely rapid reaction, from the moment that the threat is detected to the deployment of countermeasures or defensive fire. It is essential for the commanding officers to perform the OODA loop quicker than the enemy to maintain the advantage. In general terms, any increase in decision loop speed due to improvements to the CCIS system, whether human (i.e. training, more efficient task division, etc.) or decision automation, is operationally beneficial. The most general operational requirement is thus to reduce the decision loop to the minimum length of time and by at least enough to maintain operational advantage.

6.2 Command and Control System and Warfare Areas

A ship's combat system can typically be divided into five distinct warfare areas: Anti Air Warfare (AAW), Anti Surface Warfare (ASuW), Anti Submarine Warfare (ASW), Mine Warfare and Command and Control (C^2) Warfare. Command and control systems must interface with and meet the requirements of these warfare areas. The CCIS role is to manage the information that these warfare areas create through their organic sensors, along with other information sources such as data links and non-organic sensors, and present this information as a Maritime Tactical Picture (MTP) to the at sea Commander, in a manner which facilitates his ability to make decisions. It must also provide these warfare areas with the information required to conduct warfare specific functions.

The CCIS is only concerned about the information and its protocols. A buffer's responsibility is to align this data, both in time and format, so that the information management mechanisms can perform their functions based upon a common standard.

Where is the interface between the CCIS and the warfare areas? This is a question which has no easy answer. It could vary from warfare area to warfare area and there are a wide variety of opinions on this subject.

6.3 Multiple OODA Loops Model

The main source of potential integration conflict is the intrinsic existence of opposing requirements or goals between the CCIS and the warfare areas. To better understand this issue, the concept of an OODA loop, previously introduced to model the command and control process, can be extended to an overall concept of multiple OODA loops where some loops are nested in a structure having many levels, while some others operate in parallel.

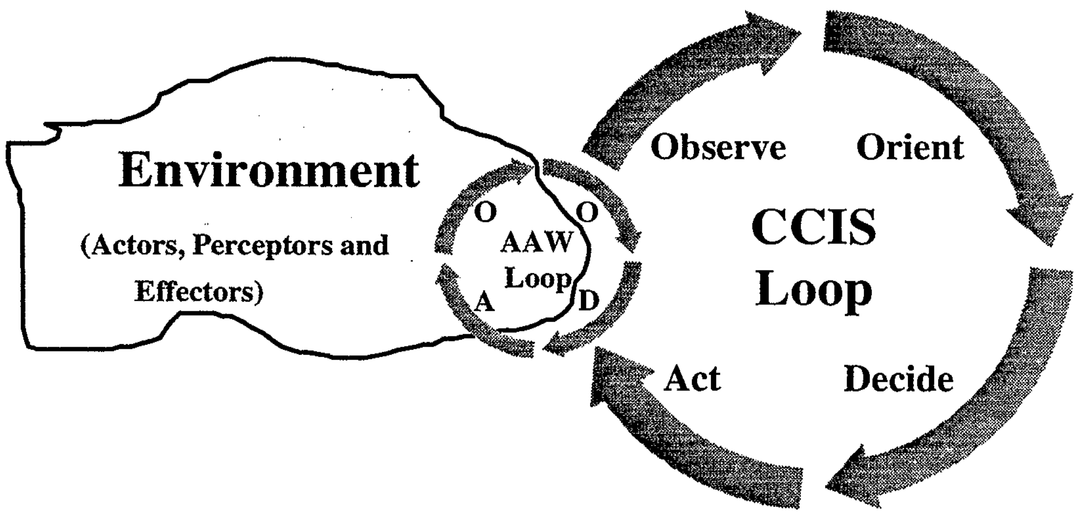

FIGURE 7 - A warfare area OODA loop within the shipboard CCIS OODA loop

The loops that are nested typically reflects a chain of command type of hierarchy where responsibilities and authorities are attached to the various levels. In this chaining framework, each individual loop is driven by output results consequent with the decide and act portion of a parent loop and produces responses that are monitored by the observe and orient portion of this same parent loop. This is illustrated with Fig. 7 where an AAW OODA loop is shown embedded within the shipboard CCIS OODA loop.

Note that the shipboard OODA loop is itself embedded within a more global OODA loop concerned with a wider area theater of operation. However, not all of the OODA loops are nested. Indeed, as shown on Fig. 8, the CCIS loop may have many subordinate loops operating in parallel, e.g., one for each warfare area. Each of these loops must be considered in its particular context of operation. A warfare area OODA loop is closer to the tactical environment than the CCIS loop. As a result, the warfare area is less concerned with what is going on in the larger scene. Reaction time is also typically shorter as one get closer to the environment where the actual battle happens.

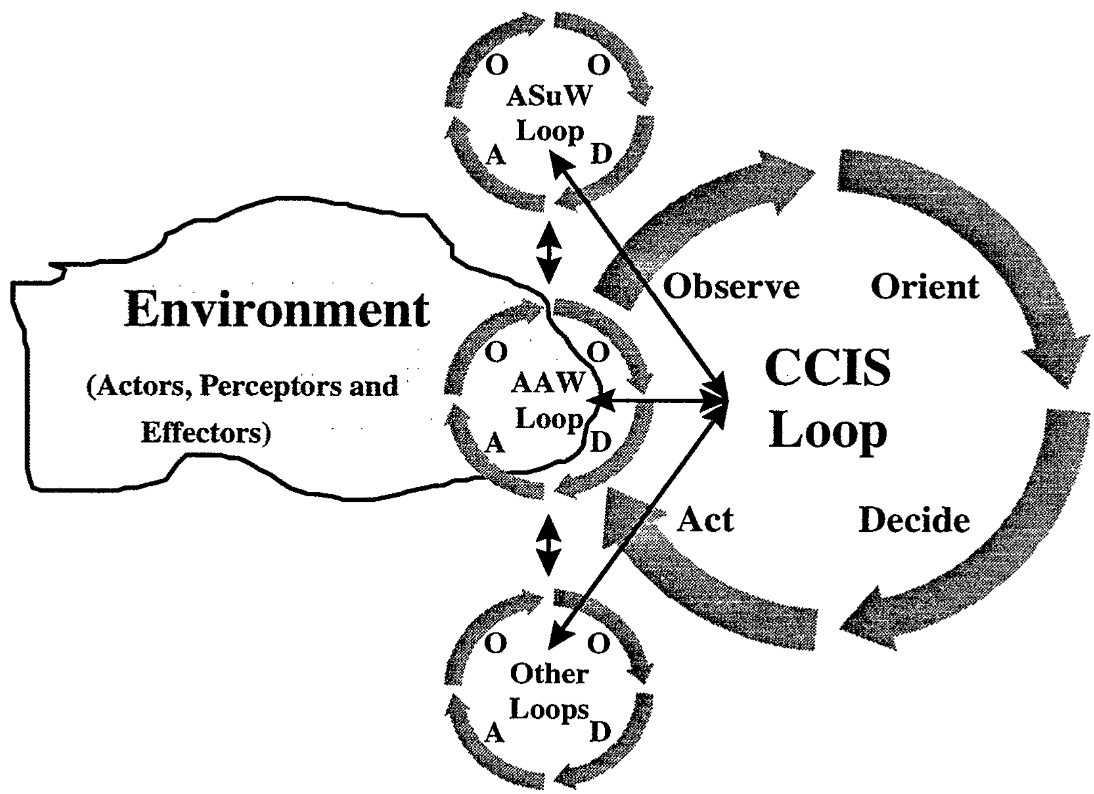

FIGURE 8 - Warfare areas OODA loops within the shipboard CCIS OODA loop

Being itself a complete loop, each individual loop of this model has a certain autonomy to observe and interpret a portion of the environment, and it has authority to make decisions resulting in actions that modify the environment. In turn, these changes in the environment have an impact on the other OODA loops. This is where some conflicts may arise.

6.4 Different Perspectives

In light of the discussion above, different integration views exist depending on the particular OODA loop that one is concerned with. From the warfare areas perspective, some sensor/weapon integration allegations often formulated are as follows:

- it is likely that it will prove to be more profitable to attempt integration of warfare area systems first before they interact with the main command and control data bus and decision system,

- doing integration at the warfare area level, at least initially, is probably more feasible than trying to do it within the CCIS,

- ship deficiencies must be attacked on two fronts: 1) improved data fusion at the command level, and 2) improved system integration at the sensor and weapon systems level.

Consequent with this view, a high priority requirement is often to provide direct integration of the sensor/weapon systems with subsequent connectivity to the ship's command and decision system.

From the perspective of command and control, guidelines or rules must be established to control the integration in the warfare areas. The integration at a lower level than the CCIS should only be done if it does not interfere with a higher level goal or if the CCIS can manage the interference, e.g., tolerate a small interference for a long period of time or perhaps a high interference for a very short period of time. The CCIS issues requests that requires an adaptive and non-conflicting level of integration, making tradeoffs when servicing two goals (i.e., the level of integration depends on the goals).

6.5 Integration Rules for Conflict/Interference Management

This section is an attempt to better characterize the relationship between the CCIS and the warfare areas in the multiple OODA loops model presented above. The followings are tentative, high-level guidelines from which one can work towards ensuring that the integration carried out in a warfare area, or the decisions made at lower levels, is not conflicting with the CCIS decision level.

In a situation where the CCIS OODA loop is the parent loop to many subordinate loops in the warfare areas, the CCIS loop must assume the task of global coordination. The Integrated Sensor Suite (ISS) and weapon systems in the warfare areas should deliver coordinated, accurate and rapid responses to direction from the CCIS.

A protocol must be defined to support a dialogue between the CCIS and the ISS. As an example, the CCIS would formulate requests to the ISS regarding a particular sensing task. Such a request would provide CCIS priorities and include items such as operational sector information, a list of specific targets of interest, any constraints on the use of sensor resources (e.g., EMCON conditions), etc. The ISS would then conceive a plan and, upon the selection of an appropriate response against a particular target (or set of targets), the ISS would provide sufficient information to the CCIS to support the proper coordination of the ISS with other combat system members. In particular, the ISS would provide a measure (e.g., a likelihood) of the ISS capability to fulfill the requested task. The answer could also include items such as sensor status information, an agenda of equipment activation and the potential interference between sensors (especially when the ISS is directed against mixed target types).

The integration of a sensor system into the combat system should not be dependent on detailed knowledge as to how the sensor system achieves its objectives.

Hence, the communication protocol must be robust enough to cope with the uncertainty in the results that the ISS could achieve for a particular task. The effect of various sensing techniques and their capabilities on the target must be provided to the CCIS only at a level sufficient for the CCIS to properly understand the implications of using specific sensors, and to direct the ISS in using techniques which will interact with the target in a way which the CCIS can exploit advantageously.

In any case, the main rule that should govern any integration effort would be to aim for the optimized overall joint effectiveness of all systems. One important issue that needs to be considered in the optimization process is the presence or absence of humans in the implementation of the multiple OODA loops. This results in a complex multi-level human-machine system. The problem is to provide real-time decision on a framework organized into layers that hierarchically decompose the functions of the system.

One of the primary difficulties is that most of the human-machine systems are characterized by dynamic, turbulent, and unpredictable demands. The system designer must allow the human operators to be able to effectively handle novel and unanticipated situations where the operators play the role of flexible and adaptive thinkers.

Dynamic resource management is the key issue in the interaction of CCIS and the warfare areas. This requires the support of real-time intelligent agents (that could be human) that are capable of reasoning about possible actions adapted to the current environment. Such agents run concurrently with their environment to respond to dynamic changes in this environment.

7.0 CONCLUSION

The concepts of sensor integration, management and data fusion were clarified in this document, in the perspective of their relationship to command and control. These are three important, distinct aspects of the coordinated use of sensor assets to support situation and threat assessment onboard ships, and consequent weapon systems actions.

As soon as more than one sensor is available in the resources at hand to tackle the problem of perception for a military system, there is potential for SIMDF. Anyone of these three concepts can be implemented by human operators alone, or it can be fully automated, or the implementation can also be any practical mix of both (i.e., a joint human-machine system). Nevertheless, the potential for SIMDF exists when multiple sensors are used together.

The appropriate integration and management of several sensors, and the intelligent use of the resulting optimum data sets through data fusion, should provide an efficient and valuable approach to support naval operations. Suitable use of sensors should provide multiple benefits.

Just as any other concept, however, sensor integration and management have their difficulties. Unfortunately, reducing interference and optimizing performance in the warfare areas may create some conflicts with other goals that a warship commander has to achieve in order to fulfill his mission. Issues were thus raised related to conflict management in the optimization of the various levels of the shipboard combat system decision tree organized as CCIS and warfare areas. Some of the main concepts of shipboard command and control were first briefly introduced. Then, a concept of multiple hierarchically organized OODA loops was described. Individual loops have a certain autonomy to observe and interpret a portion of the environment, and they have authority to make decisions resulting in actions that modify the environment and impact on the other OODA loops. An attempt was made to define guidelines required for any low level integration to be in line with the decisions made at higher levels.

The main rule that should govern any integration effort would be to aim for the optimized overall joint effectiveness of all systems. One important issue that needs to be considered in the optimization process is the presence or absence of humans in the implementation of the multiple OODA loops. This is a very complex issue that constitutes a topic for further research.

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